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Performance of markets for European renewable energy certificates

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ABSTRACT

To address the problem of information asymmetry in renewable electricity markets, European governments have introduced certification schemes. While certification appears to be an increasingly important trade mechanism for renewable electricity, it is unclear to what extent certificate markets are functioning properly. In addition, countries have chosen very different designs for their certification schemes. In order to assess the performance of markets for Guarantee of Origin certificates in twenty European countries, we construct four market performance indicators and analyse their development over 2001–2016: the churn rate, price volatility, the certification rate and the expiration rate. We also investigate the relationship between market performance and two design features of certification schemes: the public/private nature of the certifier and the presence of an international standard. We find that, despite increasing shares of renewable electricity are being certified, certificate markets suffer from poor liquidity and very volatile prices. In addition, we conclude that adopting an international standard fosters the development of certificate systems.

1. Introduction

The emission of greenhouse gases by humans is associated with significant economic and social damages (e.g. IPCC, 2014; Nordhaus, 2006). Many governments around the world are therefore attempting to reduce their economy's greenhouse gas emissions. One of the typical aims of these governments is to facilitate the change from a non-renewable to a renewable-based energy system. For example, the EU aims to produce 27% of total energy consumption in 2030 from renewable sources, coming from 17% in 2016 (European Commission, 2017). In addition to traditional policy tools such as taxes and subsidies, governments have implemented certification schemes to promote the use of renewable energy.

Certificates have been introduced to address the problem of information asymmetry in energy markets. Information asymmetry is typically present in energy markets because consumers cannot credibly distinguish between renewable and non-renewable energy. As a consequence, adverse selection may arise: consumers with a preference for renewables may end up buying less or none at all (Akerlof, 1970). Information asymmetry arises in energy markets because consumers do not experience differences between consuming renewable and non-renewable energy and production tends to occur elsewhere. The presence of networks in some important energy markets (e.g. electricity and gas) further complicates distinguishing between renewables and non-renewables because all energy in the network mingles. The purpose of certification is to bridge this informational gap. By providing consumers with information about unobservable characteristics (e.g. the production method), they are enabled to make better decisions.

In Europe, several certificate systems have been introduced for energy goods. EU directives 2009/28/EC (EU, 2009) and 2001/77/EC (EU, 2001) require member states to implement certificate systems for renewable electricity, called Guarantees of Origin (GO). GO certificates appear to be quite successful with approximately 35% of renewable electricity production receiving certification in 2015 in the EU28 countries (plus Switzerland and Norway) (AIB, 2017). The directives lay out a common framework for the design of GO certificate systems but differences between countries remain in the adopted designs. For example, differences exist in whether the certifier is a public or private organization. At the same time, unlike in Europe, certification of renewable electricity in the United States is not organised by the government at all but completely entrusted to private organizations.

The main question we address in this paper is twofold: (i) how do European markets for energy certificates perform, and (ii) how do design features of certificate systems relate to the performance of certificate markets. More specific, does it matter for the performance of a certificate market if the certifier is a public or private institution and if the certificate adheres to a common international standard. This paper contributes to the literature by providing an empirical assessment of the

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performance of certificates for energy goods in government-created markets. While other papers have generally focussed on a single country (e.g. Roe et al., 2001; Fuerst and McAllister, 2011), we analyse GO certificate markets in twenty European countries, which are comparable but differ in some critical design aspects, such as the public/private nature of the certifier.

This paper analyses the performance of GO certificate markets and the relationship between two design characteristics of certificate systems and market performance in twenty European countries over 2001–2016. We apply our analysis to the market for GOs because, unlike certificate markets for other energy carriers, relatively detailed data is available regarding quantities, prices and trade. Moreover, the electricity GO system is the largest and most ambitious certification scheme for energy goods in Europe. To investigate market performance, we analyse four market indicators: the churn rate, price volatility, the share of renewable electricity which is certified and the share of certificates that expires (i.e. is never used to claim consumption). We apply a panel data regression to a reduced-form supply and demand model to investigate the relationship between market performance and the public/private nature and presence of an international certificate standard.

Our results confirm that increasing amounts of renewable electricity receive certification. However, GO markets suffer from very poor liquidity, as measured by the churn rate and volatile prices. While the churn rate is slowly improving in the EU and most individual countries, we do not observe improvements in volatility over time. Furthermore, GO certificate markets have been in a relatively stable state of oversupply. Overall, certification has become increasingly important as a trade mechanism for renewable electricity but the performance of certificate markets remains poor. With respect to the design characteristics, we find that the presence of an international standard significantly contributes to the market volume while we also find some evidence for a positive effect of public ownership over the certifier on market volumes.

The remainder of this paper is organised as follows. Section 2 provides an overview of the literature. Section 3 discusses the methods. Section 4 describes the data. Section 5 provides the results. Finally, Section 6 discusses the conclusions and policy recommendations.

2. Literature

2.1. Information asymmetry and certificates

Several theoretical papers discuss how providing information on the basis of certificates reduce information asymmetry. In a seminal paper, Akerlof (1970) describes how information asymmetry can result in adverse selection: consumers may have a willingness-to-pay for a good with certain quality aspects (e.g. renewable electricity) but if these quality aspects are unobserved, consumers will not express their (full) willingness-to-pay in the market. Certification aims to provide consumers with information about these unobserved aspects such that consumers can confidently express their willingness-to-pay in the market. Applied to environmental goods, Dosi and Moretto (2001) and Mattoo and Singh (1994) developed theoretical models that predict a positive effect of certification on the supply of an environmental-friendly type.

With respect to the design of certificate systems, several papers question the reliability of the certifier. Mahenc (2017) and Feddersen and Gilligan (2001) discuss how the incentive of certifiers is related to providing honest information. In particular, when a certifier's goal deviates from maximizing social welfare, such as maximizing profit (Mahenc) or maximizing environmental quality (Feddersen and Gilligan), the certifier has an incentive to provide dishonest information. When certifiers are profit-maximizing firms, Lizzeri (1999) shows that competition between certifiers can results in honest certification.

There exists a broad literature that assesses the valuation of unobservable attributes of energy goods by consumers. A first group of these studies applies stated-preference methods to assess preferences for different energy goods and their (unobservable) attributes in a hypothetical buying situation. Particularly for the electricity market, there is substantial evidence that consumers prefer renewable over non-renewable electricity (see Sundt and Rehdanz, 2015 for a meta-analysis).

A second group of studies applies revealed-preference methods to investigate the willingness-to-pay for certified goods. For example, using hedonic-pricing techniques, Roe et al. (2001) show that the premium for renewable electricity in the US significantly increases with Green-E certification. More examples of revealed-preference analyses showing that consumers value environmental certification include Fuerst and McAllister (2011) for the US real-estate market and Elofsson et al. (2016) for the Swedish milk market. However, there exists also empirical evidence of environmental certification schemes that leave consumer demand unaffected. Park (2017) finds that the presence of a Korean energy-efficiency certificate does not influence the price of the certified goods. Similarly, Hornibrook et al. (2015) report that an ecolabel of the largest supermarket in the UK containing carbon information does not affect consumer choices.

Another related branch of literature discusses the physical design of certificates and the effect on consumer choice. Newell and Siikamaki (2014) find that, in addition to factual information in energy-efficiency certificates, the presence of logos (e.g. the US Energy Star or EU letter grade logo) significantly increases the willingness-to-pay of consumers for energy intensive household appliances.

2.2. European GO certificates

Several scientific papers specifically analyse the GO system. In a qualitative study, Aasen et al. (2010) conduct interviews amongst Norwegian firms to assess their perception of the informational content of GOs and find that companies have a large degree of distrust in GOs and do not believe that GOs result in any environmental effect. They propose as explanations that Norwegians perceive their electricity system as completely renewable because practically all domestic generation is renewable and that buying GOs does not affect the generation mix. In line with this, Winther and Ericson (2013), using a field experiment, found that a large group of Norwegian electricity consumers virtually did not respond to an offer from their supplier to buy GOs. From subsequent focus group sessions, the authors conclude that the Norwegians predominantly rejected the offer because they perceived their electricity as already being green. In a study on a European level, Lise et al. (2007) discuss the key elements related to operating GO systems in Europe and conclude that the functioning of GOs depends on the presence of other support schemes (e.g. feed-in tariffs) as well as electricity market fundamentals such as the level of competition and level of domestic and international trade. In addition, the authors suggest that trading GOs separately from associated electricity flows is preferred over linked trading as the former minimizes the impact on the existing electricity market while also being accurate and inexpensive. In a study on the Dutch retail electricity market, Mulder and Zomer (2016) conclude that GOs are not very effective as a policy instrument to foster investments in renewable electricity generation. The GO system has also been discussed as potential international tradable green certificate system for compliance with (national) renewable energy targets. Specifically, Ragwitz et al. (2009) find that government-based trading in GOs is preferred over company-based trading for the purpose of target compliance because, amongst other advantages, the former is more compatible with existing support schemes. In addition, Nilsson et al. (2009) investigate the political and legislative processes over time surrounding the proposition and rejection of GOs as instrument for target compliance. They find that opponents of GO trading for target compliance had stronger incentives, better coordination and a clearer position and message than proponents.

European GO markets emerged in 2001 following EU legislation which mandates each member state to set up a certification scheme for renewable electricity. The rest of this section outlines the appropriate aspects of the GO system for our paper and draws heavily on the relevant legal documentation, in particular the EU directives 2009/28/EC (EU, 2009) and 2001/77/EC (EU, 2001). European GOs (interchangeably used with certificates from here on) explicitly target reducing information asymmetry between producers and consumers of renewable electricity. GO certificates are valid for one year and expire if they are not consumed (referred to as cancelled) within this period.

While running a certification scheme is mandatory, countries have considerable freedom in choosing their own certificate system design. This has led to differences between countries with respect to quality assurance and market organization.

Each country is required to appoint a certifier which is responsible for issuing and cancelling certificates and facilitating trade. More than one certifier may be appointed but each certifier is responsible for a non-overlapping geographical area. As a result, only one monopolistic certifier is active in most countries, except for Greece and Belgium where multiple regional monopolists are active.

Countries may freely decide to appoint a public or private certifier. France, Czech Republic and Portugal are the only countries with a currently or previously active private certifier.

A number of countries have adopted a common international standard for their GO certificates. This EECS-standard standardizes the information provided in the certificate and rules regarding issuance, cancellation and trade. EECS certificates are traded through a central electronic hub which is operated by the Association of Issuing Bodies (AIB), an association representing the GO certifiers. The presence of a standard facilitates international trade through regular advantages of standardization: it establishes a quality level of certificates and eases comparison of certificates from different origins. The presence of a central trading hub reduces transaction costs further because, absent a central hub, each country may set their own import and export procedures.

With respect to market organization, the EU rules try to foster an integrated European market for certificates. Countries are obliged to accept the import of GO certificates from other countries.[1] However, countries are free to set export restriction, which is done in practice by two countries: Austria does not allow the export of certificates obtained by a generator that has received state support and Spain requires any revenue from exporting certificates to be transferred to the government, which functions as an export ban.

Several countries exclude producers from obtaining certificates at all when they received state support. This concerns Croatia, France, Germany, Ireland and Luxembourg. The typical rationale for this policy is that, as the state support intends to provide a regular profit for the producers, additional revenues from certification would be windfall profits.

Table 1 summarizes the design choices of the countries we analyse. In addition to the presence of the international standard and the certifier's public/private character, this table reports if a country has export or certification restrictions in place.

Table 1
Design characteristics of national GO certification schemes in European countries.

	Implementation of international standard	Nature certifier	Export restrictions	Certification restrictions
Austria	2004	Public	Yes	No
Belgium	2006	Public	No	No
Cyprus	2014	Public	No	No
Croatia	2014	Public	No	Yes
Czech Republic	2013	Private (2013-current)	No	No
Denmark	2004	Public	No	No
Estonia	2010	Public	No	No
Finland	2001	Public	No	No
France	2013	Private (2013-current)	No	Yes
Germany	2013	Public	No	Yes
Iceland	2011	Public	No	No
Ireland	2015	Public	No	Yes
Italy	2013	Public	No	No
Luxembourg	2009	Public	No	Yes
Netherlands	2004	Public	No	No
Norway	2006	Public	No	No
Portugal	Not implemented	Private (2013–2015)	No	No
Spain	2016	Public	Yes	No
Sweden	2006	Public	No	No
Switzerland	2009	Public	No	No

3. Method

We assess the performance of certificate markets by constructing four markets indicators (Section 3.1): the share of renewable electricity with a certificate (the certification rate), the churn rate, price volatility and the share of certificates that expires (the expiration rate). We relate design features of certification schemes to market performance by estimating a reduced-form supply and demand model based on quantities and market fundamentals (Section 3.2).

3.1. Market performance

Our four performance indicators relate to primary market outcomes, such as quantities, prices and trade. Firstly, we assess the certification rate, a measure of output. Generally, maturing markets are associated with increasing output volumes. As the amount of certification is related to the amount of renewable electricity (which has recently been increasing in many countries) we analyse the share of certified renewable electricity instead of the absolute volume. The certification rate (cr) is calculated as:

$$cr_{ti} = \frac{Q_{ti}}{RE_{ti}}, \tag{1}$$

where Q refers to the volume of issued certificates, RE to the output of renewable electricity (both in MWh) and t and i to time and country.

Secondly, we assess market liquidity by evaluating the churn rate. The churn rate is frequently used as an indicator for liquidity in physical and financial markets (e.g. Heather, 2015; ACER/CEER, 2017). It indicates how often a product is traded before it is consumed. The churn rate may be defined as the ratio of traded volume to final consumption. A higher churn rate indicates a higher level of market liquidity. For commodity markets, a threshold above which a market is generally considered mature is 10 (Ofgem, 2009).

We construct three different churn rates in order to cope with the unavailability of individual transaction data. Our dataset includes aggregated data for the number of issued, cancelled, domestically traded, imported and exported certificates per calendar year.[2] As certificates

[1] Expected fraud or 'system weakness' is a valid reason to deny imports of certificates from a country.

[2] The AIB provides certification data twice: (i) by the time of production and (ii) by the time of transaction. Data provided by the time of production (i) refers to when the electricity related to the certificate was produced while (ii) refers to when the certificate transaction took place, e.g. the year a certificate was issued. Discrepancies arise due to the administrative processing time of certifiers. As a result, renewable electricity produced in year t may receive a certificate in year t + 1. Availability of data differs between the two statistics. E.g. data for issuance and expiration of certificates by time of transaction does not exist prior to 2009 while it is available for all years by time of production.

expire after one year, certificates issued in a given calendar year may have been cancelled in the same or next calendar year. The same goes for imports. Imports in one year may have been cancelled in the same or next calendar year. Similarly, transactions and cancellations in one year can relate to certificates issued in the previous or same year. To overcome this difficulty, we constructed three churn rates that differ in the approach to calculate final demand for consumption.

The first churn rate (x^1) is based on the domestically traded volume and the number of issued and imported certificates in the same calendar year. The number of issued and imported certificates jointly determine the tradable volume in a market. For individual countries, the first churn rate is given by:

$$x_{ti}^1 = \frac{T_{ti}}{Q_{ti} + IM_{ti}}, \tag{2}$$

where T is domestic transfers and IM imported certificates.

The second churn rate (x^2) is based on current year's traded volume and the number of issued and imported certificates in the previous year:

$$x_{ti}^2 = \frac{T_{ti}}{Q_{t-1,i} + IM_{t-1,i}}. \tag{3}$$

The third churn rate is based on the current year's traded volume and number of cancelled certificates (C):

$$x_{ti}^3 = \frac{T_{ti}}{C_{ti}}. \tag{4}$$

The first churn rate relates current trade to current production, the second relates current trade to previous production and the third relates current trade to current consumption. There appears to be no good reason to prefer one over the others with our dataset. Therefore, for individual countries, we will report on the basis of the simple average of these three churn rates (xr):

$$xr_{ti} = \frac{x_{ti}^1 + x_{ti}^2 + x_{ti}^3}{3}. \tag{5}$$

For the whole region (the international GO market), we cannot use (2), (3) and (4) to calculate the churn rate because, for all countries combined, imports/exports are equal to zero since all registered imports and exports are between countries within the GO scheme. Therefore, when considering the whole region, imports/exports should be regarded as transactions. The available volume for final consumption is simply aggregated issued or cancelled volume. To take this into account, we calculate slight variations on (2), (3) and (4) for the whole region (indicated by the prime superscripts):

$$x_t^{1'} = \frac{\sum_{i=1}^n T_{ti} + \sum_{i=1}^n IM_{ti}}{\sum_{i=1}^n Q_{ti}}, \tag{2′}$$

$$x_t^{2'} = \frac{\sum_{i=1}^n T_{ti} + \sum_{i=1}^n IM_{ti}}{\sum_{i=1}^n Q_{t-1,i}}, \tag{3′}$$

and

$$x_t^{3'} = \frac{\sum_{i=1}^n T_{ti} + \sum_{i=1}^n IM_{ti}}{\sum_{i=1}^n C_{ti}}, \tag{4′}$$

where n refers to country. We report again on the basis of the simple average:

$$xr_t' = \frac{x_i^{1'} + x_i^{2'} + x_i^{3'}}{3}. \tag{5′}$$

We cannot compare this churn rate to the churn rate of individual countries because (5′) will always tend to be higher than (5). This is inherent to increasing the geographical span of the market such that imports/exports become part of traded volume instead of the available volume for consumption (increasing the churn rate's numerator and decreasing the denominator). To calculate a churn rate for the whole region which is comparable to the churn rate for individual countries, we may take the cancelled-volume-weighted average of (5):

$$xr_t'' = \frac{\sum_i^n xr_{ti} * C_{ti}}{\sum_i^n C_{ti}}. \tag{6}$$

Thirdly, we assess the development in certificate price volatility. Price volatility is an indicator for fluctuations in the price, i.e. price uncertainty. Generally, improvements in market maturity and liquidity are associated with decreasing price volatility (ACM, 2014). In mature, liquid markets, single events that affect supply or demand (e.g. a power plant outage) are absorbed by the market with less profound price effects as compared to illiquid markets. A common measure of price volatility is the standard deviation of price changes (e.g. Regnier, 2007). Here, we calculate annual price volatility as the standard deviation of monthly relative price changes.

Fourthly, we assess the expiration rate. If certificates are not used within one year, they expire and are not used to prove the consumption of renewable electricity. A high expiration rate is an indicator for low demand from end-users for renewable electricity on the basis of a certificate. We calculate the expiration rate (er) by dividing the volume of expired certificates (E) by the volume of issued certificates:

$$er_{ti} = \frac{E_{ti}}{Q_{ti}}. \tag{7}$$

Larger values for this indicator are associated with increasing levels of excess supply.

3.2. Relating certificate system design features to market performance

To relate the two design features to market performance, we estimate a reduced-form supply and demand model of the quantity of issued certificates on the wholesale market. The intuition behind the model is that changes in the certified volume are caused by changes in fundamental demand and supply factors. The quantities we observe reflect equilibrium prices, i.e. points where the demand and supply curves intersect. We are not able to isolate the effect of the design features on supply or demand, but we are able to test whether they have an effect on the market outcome, which is our main interest. We estimate the model $Q_{ti} = \phi(\boldsymbol{X}_{ti}, \boldsymbol{Y}_{ti}, \boldsymbol{Z}_{ti})$ where $\boldsymbol{X}$ contains the design characteristics and $\boldsymbol{Y}$ and $\boldsymbol{Z}$ the fundamental supply and demand variables. We will now first elaborate on these characteristics and fundamentals (Section 3.2.1) and then discuss our empirical model (Section 3.2.2).

3.2.1. Design characteristics and market fundamentals

The presence of an international standard, as opposed to a domestic standard, facilitates international trade through reducing transaction costs (e.g. Blind and Jungmittag, 2005; Swann et al., 1996). As a result of more international trade, consumers have a greater number of products to choose from (which is particularly relevant if consumers care about the production location) and competition between producers increases. Overall, while some countries may experience increases and others decreases, because of standardization, the quantity traded in the market increases.

The public/private nature of a certifier can be related to market performance through the reliability of certification and the certification fee. Assuming that governments are more inclined to maximize social welfare than firms, private certifiers have a greater incentive to provide dishonest certification than public certifiers by certifying grey electricity as green, thereby increasing revenues (Mahenc, 2017). This puts upward pressure on the supply of certificates. However, as Mahenc points out, consumers may reasonably expect this type of behaviour from a profit-maximizing certifier. As a result, consumers may trust a private certifier less, putting downward pressure on demand. Also when certification is honest, monopolistic profit-maximizing certifiers may affect market outcomes by exercising market power and selecting a higher certification fee when left unregulated.

An important factor affecting the demand for certification is the output of renewable electricity, which in turn largely depends on meteorological factors. The output of these generators is typically eligible for certification such that increases in renewable electricity production directly increase the potential certified volume (EU, 2009). The installed capacity of renewable electricity generators determines the maximum output of renewable electricity. Meteorological conditions such as the wind speed, rainfall and solar radiation determine the actual output at a given moment.

Restriction policies on certification and exports affect the demand for certificates on a wholesale level. Governments that limit certification to non-supported generators put downward pressure on the demand since certification becomes uninteresting to generators when subsidies exceed certificate prices. Export restrictions limit the possibilities to market the certificate for a generator, putting downward pressure on expected benefits from certification and therefore demand for certificates.

The price of electricity is expected to be relevant for the certified volume through the demand for certificates. The final price of (certified) renewable electricity depends on both the certificate price and the electricity wholesale price (BEUC, 2016; Mulder and Zomer, 2016). The certificate price represents the green premium for renewable electricity as certificates and physical electricity are traded separately. Retailers of renewable electricity need to procure both physical electricity and a certificate. Therefore, increases in the price of electricity raise the final costs of renewable electricity for end-users, putting downward pressure on the demand for renewable electricity and certificates.

Another important demand side variable is the level of income. As income rises, both residential and industrial end-users increase their demand for (renewable) electricity (Kamerschen and Porter, 2004). Increases in the use of renewable electricity put upward pressure on the demand for certificates as more certificates are required for end-users with certificate-based renewable electricity contracts.

The supply curve on the certificate wholesale market is somewhat peculiar. The marginal cost of certification by certifiers is nearly zero as it is largely an automatized process and has no variable inputs besides digital storage space. In a competitive market, the (short-run) supply curve would therefore be a flat line at a price of zero. However, by EU rules, GO certifiers are national/regional monopolists giving these firms market power. As these firms tend to be regulated companies, the extent to which market power can be exerted depends on the regulatory framework. In contrast to private certifiers, public certifiers have few incentives to exert market power. But other forms of regulation than public ownership can limit the exertion of market power as well, such as appointment by tendering. Apart from the public/private nature of certifiers, we have no information about the type of regulation in individual countries.

3.2.2. Empirical model

We estimate a panel data model of the quantity of issued certificates Q in year t and country i, as a function of supply and demand fundamentals and the two design characteristics. The design characteristics are represented by two dummy variables indicating whether the international standard is present (ST, equal to 1 if present) and the certifier is public or private ($priv$, equal to 1 if private). The demand and supply fundamentals we control for are total renewable electricity generation (QRE), the consumer electricity price (PE) and a real GDP index (Y). Finally, we include two certification-policy dummy variables: export restrictions (exr; equal to 1 if present) and certification restrictions (cer; equal to 1 if present). The equation we estimate is:

$$Q_{ti} = \alpha_1 + \alpha_2 ST_{ti} + \alpha_3 priv_{ti} + \alpha_4 QRE_{ti} + \alpha_5 Y_{ti} + \alpha_6 PE_{ti} + \alpha_7 exr_{ti} + \alpha_8 cer_{ti} + c_t + u_{ti}, \tag{8}$$

where c is an unobserved, time-invariant individual effect. Here, this may capture differences between countries in preferences for renewable electricity (Sundt and Rehdanz, 2015). The (endogenously determined) certification cost (i.e. the price in the wholesale market) is not included in the empirical model as information for individual countries is largely unavailable.

We also estimate an alternative specification based on Eq. (8) where we consider a potential effect of the 2009 EU renewable energy directive on certificate market volumes. As this directive mandates countries to make individual plans to foster renewable energy, we add to the model a set of country-period dummies D that are equal to 1 in country i after the reform (2009–2015) and zero otherwise. This captures, for example, differences in renewable energy policy situations before and after the reform within countries, taking into account that countries may have reacted differently and consequently experienced different developments. Because of the dummy structure, these variables may also capture other non-included factors that vary between the two periods, such as an increase in the willingness-to-pay for renewable electricity in a country. The second model we estimate is:

$$Q_{ti} = \alpha_1 + \alpha_2 ST_{ti} + \alpha_3 priv_{ti} + \alpha_4 QRE_{ti} + \alpha_5 Y_{ti} + \alpha_6 PE_{ti} + \alpha_7 exr_{ti} + \alpha_8 cer_{ti} + \sum_{i=1}^{20} \beta_i D_{ti} + c_t + u_{ti}. \tag{9}$$

4. Data

GO markets are not very transparent. While quantity data is publicly available through the AIB, price data is not publicly available, partly because trade in GOs occurs only bilaterally or via brokers. Market players appear to corroborate this lack of transparency in GO markets (Greenfact, 2018). Nevertheless, we were able to obtain a comprehensive dataset to analyse the functioning of GO markets.

We obtain data from various sources for 20 European countries: Austria, Belgium, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Iceland, Ireland, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden and Switzerland. We include this set of countries as they have implemented the EU GO regulations while certification data is available for them in the AIB database.[3] Certification data is available from 2001 to 2016 while availability for other variables is sometimes limited.

GO certification data comes from the AIB and includes annual data on issuance, cancellation, expiration, domestic trade, imports and exports. The publicly available dataset aggregates certification data for all types of electricity, including fossil and nuclear. For our analysis, the AIB has provided separated data for fossil, nuclear and renewable certificates. We almost exclusively use data for renewable electricity in this paper. We encountered several shortcomings in the certification data: (i) illogical reporting: Croatia cancelled and expired certificates for the first time in 2014 while the first certificates were issued and imported in 2015 and (ii) incomplete reporting: Sweden and Austria issue non-tradeable type of GOs and these are not included in the AIB database. Moreover, the database includes some entries which do not relate to GO certificates. The database reports one non-zero entry for the UK. Consultation with the AIB learned that this entry concerns RECS certificates instead of GOs. RECS is a voluntary certification scheme which used to be administered by the AIB.

We made three initial adaptations to the AIB database. First, we remove Slovenia from the database because data is not reported out of fears of exposing the trading position of a market participant. Second, we remove the UK from the database since the reported activity concerns RECS certificates instead of GOs. Third, we aggregate the data of the four Belgian certifiers to obtain a single observation for Belgium.

Our GO price data comes from Greenfact. Greenfact is a market-monitoring firm which obtains prices by consulting market participants.

[3] Non-EU member states Norway and Switzerland have also implemented the EU GO legislation.

Our dataset includes monthly volume-weighted average prices for certificates. It further specifies the production year, certificate origin (country/region, e.g. Nordic), production technology and trade volume. Observations range from 2011 to 2017 but periods are substantially shorter for most of the products. In order to determine which prices are comparable, we first distinguish between spot and forward contracts. A spot contract is defined as contract with a production year equal to or one year prior to the contract's transaction year. This seems logical considering that certificates expire after one year. Most of the trades in the database are spot contracts. We further distinguish products by country/region of origin and production technology.

From Eurostat, we extract the real annual GDP index and the electricity price for all countries, except for Switzerland, which is not reported. We use the bi-annual household electricity price and take the simple average to estimate the annual average electricity price. Some years are missing for Croatia, Estonia and Iceland. For Switzerland, we use the average annual end-user price, as reported by the Swiss Federal Office of Energy until 2015. All prices expressed in Swiss Francs are converted into Euros using the annual average exchange rate according to Eurostat.

We obtain annual data on the production of renewable electricity for EU-countries and Norway from Eurostat (available until 2015). For Switzerland, we obtain this data from the IEA.

Information about implementation of the international standard is taken from Fact Sheet 17 on the AIB website. We inspect the websites of the (former) national certifiers to determine whether they are public or private institutions.

Table A.1 in appendix A reports all descriptive statistics, except for certificate prices, which are reported in Table A.2.

5. Results and discussion

This section first discusses the results of the four market performance indicators (Sections 5.1–5.4) and consequently the results of our analysis of the relationship between the design features and market performance (Section 5.5).

5.1. Certification rate

GO certification of renewable electricity has become increasingly important in the EU since the start of operation in 2001. Fig. 1 shows the development of the certification rate of renewable electricity, fossil electricity and total electricity in all countries combined. The certification rate of renewable electricity increased from 0.2% to 35.5% from 2001 to 2015. Certification of fossil electricity is much less important, as indicated by the low certification rate of 1.7% in 2015.

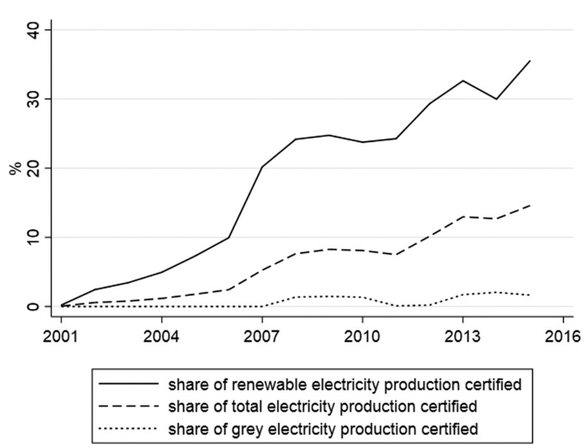


Fig. 1. The electricity certification rate in Europe, 2001–2015.
Sources: AIB, Eurostat, IEA.

There are significant differences between countries in the relative importance of certification. Fig. 2 shows the development of the certification rate in individual countries by comparing the average certification rate between four periods: 2001–2004 with 2005–2008 (panel

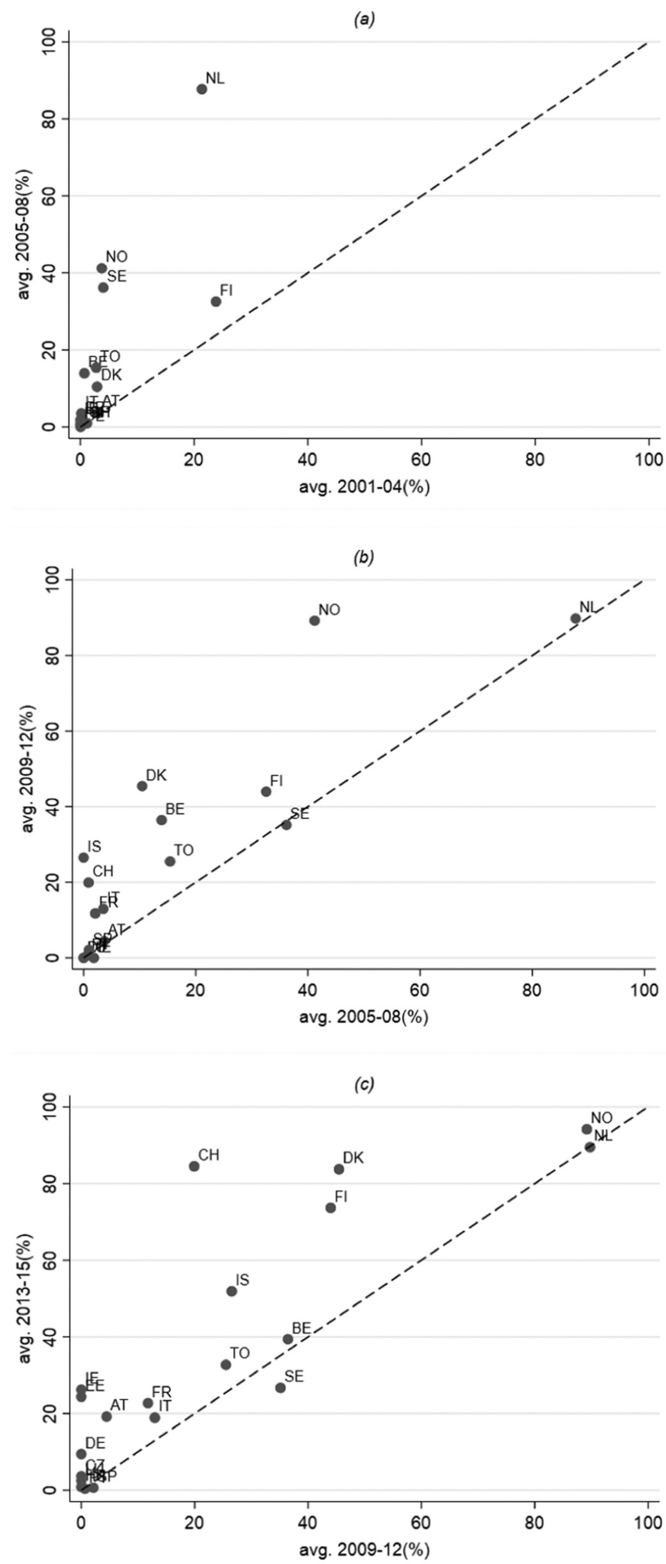


Fig. 2. The certification rate per country, 2001–2015. Note: Each plot compares the 4-year average with the preceding 4-year average from 2001 to 2015 (one 3-year period: 2012–2015).
Source: own calculations, AIB, Eurostat, IEA.

Table 2
Summary statistics of three churn rates for individual countries.
Source: own calculations, AIB.

	xˆ1	xˆ2	xˆ3
Mean	0.21	0.36	0.46
Standard deviation	0.50	0.85	0.85
Minimum	0.00	0.00	0.00
Maximum	5.69	7.22	6.71

Note: The first churn rate approximates final consumption by the number of issued certificates (xˆ1), the second by the number of issued certificates in the previous year (xˆ2) and the third by the number of cancelled certificates (xˆ3).

a), 2005–2008 with 2009–2012 (panel b) and 2009–2012 with 2013–2015 (panel c). Years without an active certifier are excluded when calculating averages. Country names are represented by two-letter abbreviations. In these planes, countries on the diagonal lines reflect equal observations for the two considered periods, hence no change in the relative amount of certification.

In most countries, the amount of certified renewable electricity either increases or remains stagnant between two periods. In all periods, several countries are located above and quite distant from the diagonal line, indicating a considerable increase in the certification rate. Certification has become particularly important (> 70%) in Denmark, Finland, the Netherlands, Norway and Switzerland. Most other countries have experienced increases as well.

Only one observation lies considerably far below the diagonal: Sweden in panel c, which is due to a data issue. Due to a legislative change, part of Swedish certificates became ineligible for export in 2010 and these certificates are not included in the database. The rest of the observations that lie below the diagonal (4 out of 52) are countries with very low certification rates (< 2.5%).

5.2. Churn rate

Table 2 provides summary statistics of the three different churn rates for individual countries (corresponding to Eqs. 2–4).[4] The three churn rates all have very low averages but are somewhat different from each other. The mean of the churn rate based on cancellations (0.46) is more than double the mean of the churn rate based on current year's issuance (0.21). The churn rates based on previous year's issuance and cancellations are more similar, both in terms of the means and standard deviations. This also holds for most individual years (not reported here). This suggests that cancellations tend to follow previous year's issuance closer than current year's issuance.

The churn rate remains low in each country. Fig. 3 compares the simple average of the three churn rates between four time periods: 2001–2004 with 2005–2008 (panel a), 2005–2008 with 2009–2012 (panel b) and 2009–2012 with 2013–2016 (panel c). To facilitate readability, observations in the origin, reflecting zero domestic trade in both periods, are omitted. In the period 2009–2012, Austria is the first country where the churn rate exceeds 1 (1.4). The highest churn rates are observed in Estonia (2.2) and Italy (2.5), both in the most recent period. Other countries do not experience churn rates above 1.5 in any of the periods.

Fig. 3 reveals mixed growth experiences over time between countries. Several countries have experienced steady increases in the churn rates since the beginning, such as Norway and Denmark. A few countries have experienced decreases, particularly in the period 2009–2012, such as Italy and France. In the most recent period, the churn rate has

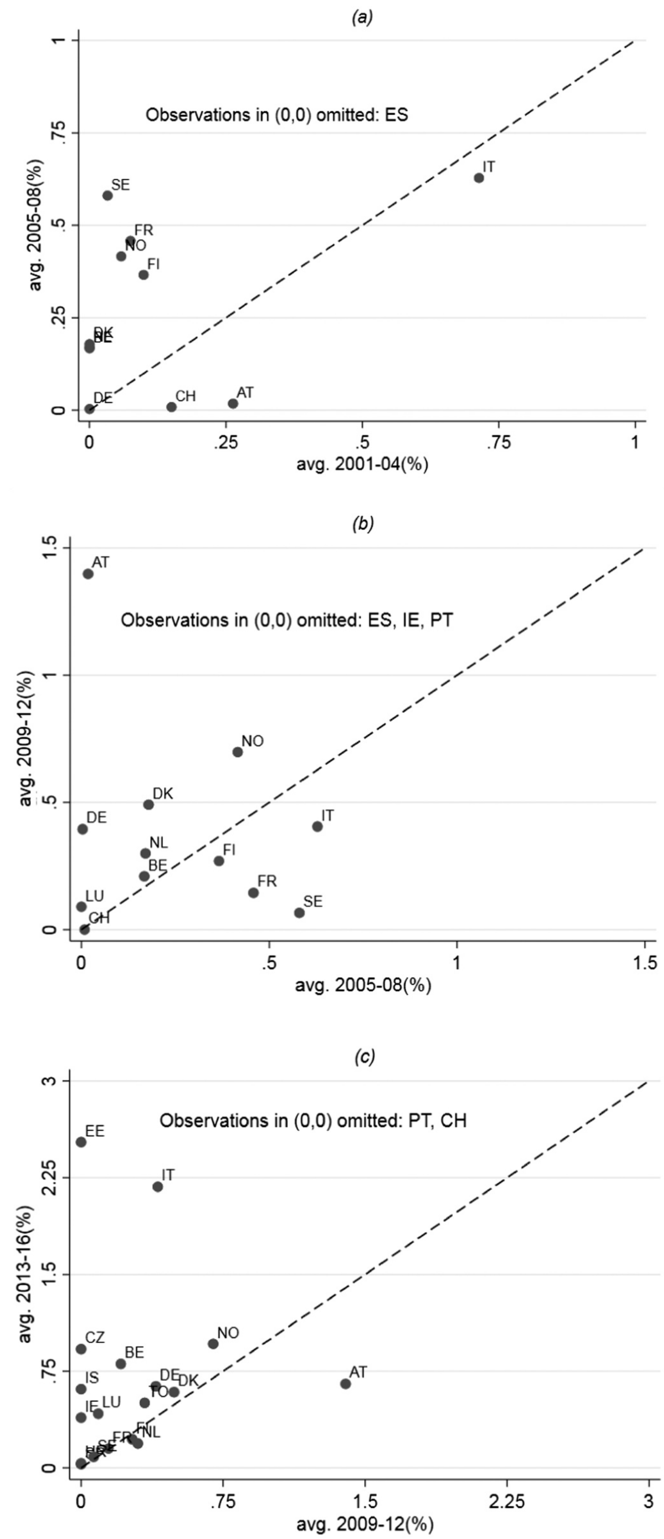


Fig. 3. Churn rate per country, 2001–2016. Note: Each plot compares the 4-year average with the preceding 4-year average from 2001 to 2016. Countries in (0,0) have active certification schemes. Differences in scaling are chosen to enable identification of individual countries in graphs.
Source: own calculations, AIB.

been increasing in almost all countries. Nevertheless, the levels remain very far below 10 in each country.

For all countries combined, the churn rate displays an increasing trend over time (Fig. 4). From 2002–2016, the churn rate and country-

[4] After calculating the churn rates, 6 curious observations in 5 countries were deleted (Czech Republic, Finland, Germany, Italy, and Iceland). See Appendix B for clarification.

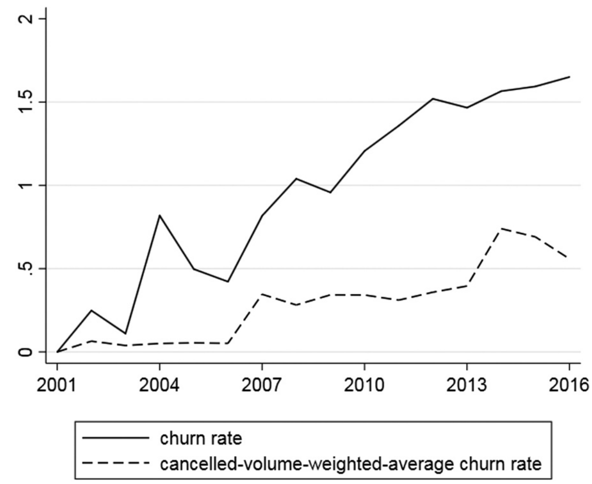


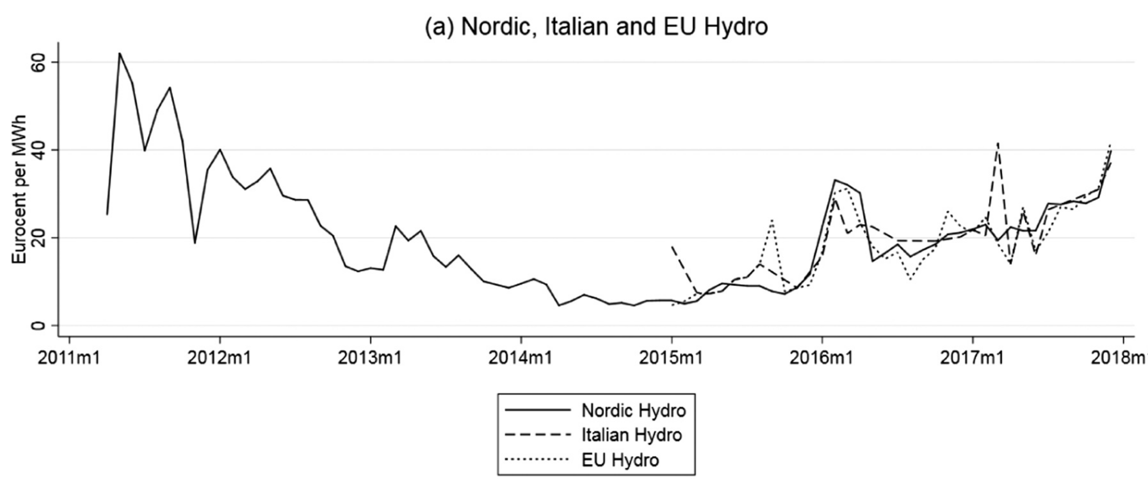
Fig. 4. Churn rate in all countries combined, 2 types, 2001–2016.
Source: own calculations, AIB.

weighted average churn rate increased on average 14.5% and 16.7% per year, respectively. However, the levels of 1.65 (whole area) and 0.56 (country-weighted average) in 2016 are very poor and far from levels generally considered as liquid.

5.3. Price volatility

Fig. 5 shows the development of spot prices for products for which we have most observations: Nordic hydro, Italian hydro and EU (i.e. unspecified) hydro (panel a) and EU biomass, EU solar and EU wind (panel b). At first glance, there appears some co-movement but, at times, peaks in some prices are hardly reflected in the other prices. Correlation coefficients of the spot prices (see Table C.1 in Appendix C) suggest that, to some extent, certificates from different countries and technologies have their own price dynamics. Some products are strongly correlated but other products are uncorrelated or even negatively correlated. This confirms that a product division on the basis of region and technology is appropriate.

The volatility in certificate prices is relatively high. Table 3 reports the volatility in monthly spot prices. Volatility differs by product but is quite high for all products. In 2017, volatility ranged from 3.4% for Dutch wind certificates (effectively based on only two price-change observations) to 105.6% for Belgian wind certificates. The volatility in Nordic hydro certificates, one of the most liquid products, was 14.3%. Over time, volatility has been fluctuating but the patterns do not appear to suggest a stable improvement.



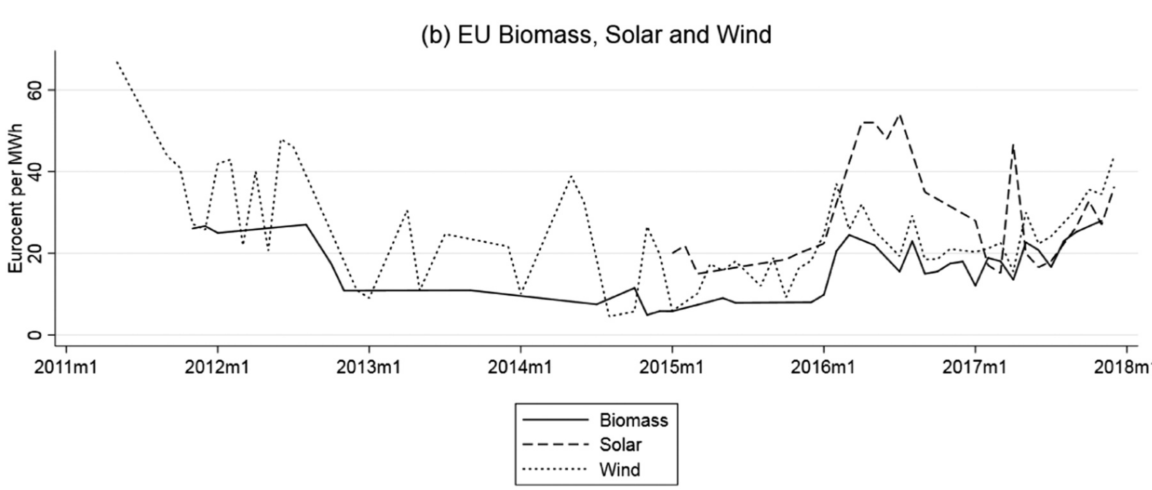


Fig. 5. Spot prices for hydro GO certificates in three countries (panel a) and for GO certificates in the EU (i.e. not specified by country) for three different technologies (panel b), 2011–2017, per month.
Source: Greenfact.

Table 3
Volatility in monthly spot prices (annual averages), 2011–2017.

Country	Technology	2011	2012	2013	2014	2015	2016	2017
Nordic	Hydro	66.6%	13.4%	31.2%	22.2%	19.0%	34.5%	14.3%
Belgium	Biomass							63.9%
	Solar							84.8%
	Wind							105.6%
EU (unspecified)	Biomass		22.2%		54.4%	8.9%	41.7%	33.3%
	Hydro					33.6%	40.7%	34.4%
	Solar					23.1%	10.4%	78.1%
	Wind	16.0%	69.0%	32.6%	198.0%	54.7%	30.0%	34.3%
Italian	Hydro					15.7%	47.9%	59.8%
Netherlands	Biomass							30.9%
	Wind							3.4%
Switzerland	Hydro							28.1%

Note: Volatility is measured as the standard deviation of monthly relative price changes.

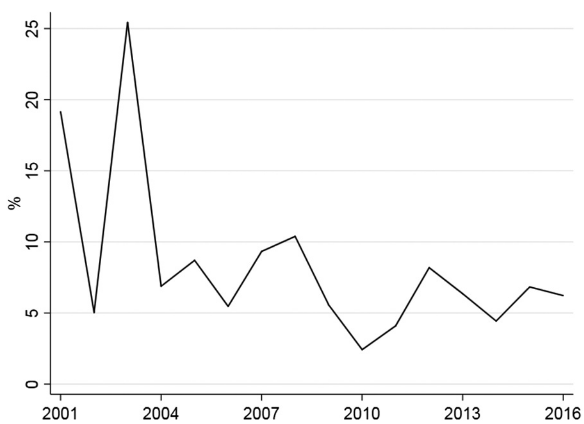


Fig. 6. Expiration rate, all countries combined, 2001–2016.
Source: own calculations, AIB.

5.4. Expiration rate

Fig. 6 depicts the expiration rate per year from 2001 to 2016 in the whole region. The amount of expired certificates ranged between 5% and 25% from 2001 to 2003. From 2004–2016, the expiration rate appears more stable, being on average 6.5% and ranging from 2.4% to 10.4%. This indicates that, while most certificates are cancelled, a substantial amount of certificates expires and therefore remains unused for proving the consumption of renewable electricity.

Fig. 7 compares the expiration rate in individual countries between four periods: 2001–2004 with 2005–2008 (panel a), 2005–2008 with 2009–2012 (panel b) and 2009–2012 with 2013–2016 (panel c). We exclude the expiration rate in Luxembourg in 2011, 2012 and 2014 because they exceed 100%, which should be impossible. We suspect this is caused by inaccuracies in the database. Interestingly, the number of countries without expirations decreases from 9 in the first period (Austria, Belgium, France, Germany, Italy, Netherlands, Spain and Switzerland) to 2 in the last period (Austria and Portugal). Denmark and Norway have very high expiration rates ($>$ 38%) in the initial years, but these decrease to less than 5% in the most recent period. From 2009–2012, the expiration rate decreases to levels below 8% in all countries except for Denmark. However, in the most recent period, expirations increase again in the majority of countries. Interestingly, the expiration rate appears high in major importing countries such as Germany and the Netherlands.

5.5. Certificate design features and market performance

Our panel, consisting of 20 countries with data from 2001 to 2015, is unbalanced due to the fact that some countries start operating a certification scheme after 2001. There are also several years missing for the electricity price in Croatia, Estonia and Iceland.

We apply a within estimation procedure to estimate the coefficients of Eqs. (8) and (9) because the time-invariant individual effects may be correlated with some of our regressors. For example, one could well imagine that differences in preferences for renewable electricity between countries are correlated with income (Mozumder et al., 2011) or renewable electricity generation. As a consequence, we do not obtain estimates for the certification and export restriction variables as these did not vary over time in practice.

Statistical tests suggest that the assumption of white-noise errors is not satisfied. Autocorrelation tests, as proposed by Wooldridge (2002), do not suggest that autocorrelation is present. However, likelihood-ratio tests suggest that the errors are heteroskedastic. Therefore, we compute White standard errors. We opt for this solution rather than computing cluster-robust standard errors because our sample consists of 20 clusters, much lower than the threshold for reliable inference on the basis of cluster-robust standard errors of 50 according to Cameron et al. (2008).

Table 4 reports our estimation results where Model A reports the results of the model in Eq. (8) (columns 2,3 and 4) and Model B reports the results of the extended model in Eq. (9) (columns 5, 6 and 7). Note that model B has a considerably higher explanatory power (within R-squared of 0.710 vs. 0.223 in model A) while the signs, sizes and significance levels of our estimates are largely consistent between the two models.

The estimates imply that the presence of the international standard positively influences the market volume. The estimated coefficients are 14.07 and 8.95 respectively for model A and B which both are significant at a 0.01 confidence level. This effect is substantial: on average, the presence of the international standard positively affects the volume of issued certificates by 9–14 TWh. The increase in volume is approximately equal to 57–90% of the median volume of issued certificates in 2016.

The estimated effect of having a private instead of a public certifier is negative in both specifications and marginally significant (p-values of 0.07 and 0.12 in models A and B respectively). The estimated coefficients of -5.88 and -4.51 are considerable in size in both models. Although these estimates are less statistically significant, this may point to a negative effect of private certifiers on market volumes. A possible explanation for this negative effect may be that, despite regulatory

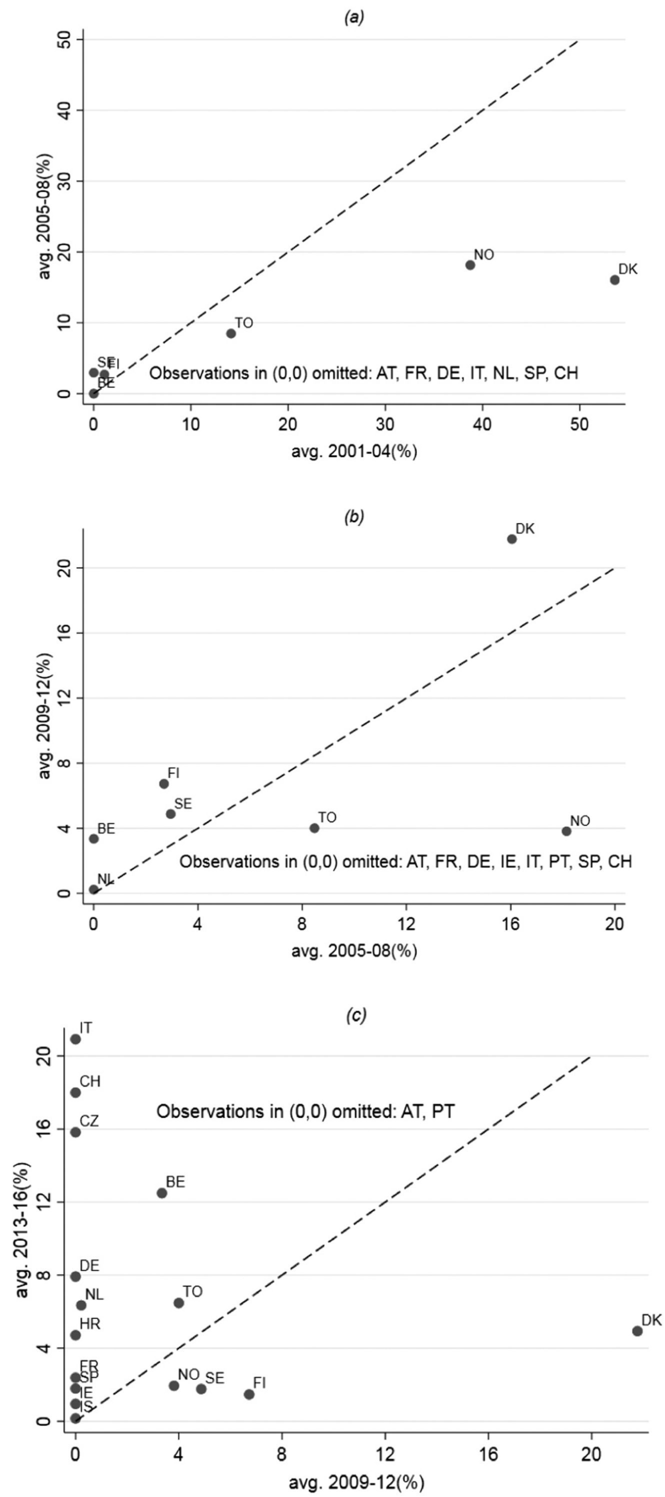


Fig. 7. Expiration rate per country, 2001–2016. Note: Each plot compares the 4-year average with the preceding 4-year average from 2001 to 2016. Countries in (0,0) have active certification schemes. Differences in scaling are chosen to enable identification of individual countries in graphs.
Source: own calculations, AIB.

measures in some countries, private certifiers are able to exert market power, resulting in higher certification fees and lower market volumes. Supportive to this explanation, it appears from AIB (2015) statistics that three out of the four highest variable certification fees in 2015 were charged by private certifiers. Another reason could be that end-users regard signals from private certifiers as less trustworthy, as noted by Mahenc (2017).

As expected, the generation of renewable electricity has a strongly significant positive effect on the market volume. The estimated coefficient for the GDP index is positive, conform expectation, and marginally significant. Our estimates for the coefficient of the electricity price have contrasting signs in the two models but are highly insignificant.

Table 4
Fixed effects panel data estimation, 2001–2015. Dependent variable: Volume of issued certificates (TWh).

	Model A			Model B		
	Coefficient	Standard error	p-value	Coefficient	Standard error	p-value
International standard	14.07***	2.955	0.000	8.95***	2.955	0.003
Private certifier	− 5.88*	3.181	0.066	− 4.51	2.888	0.120
Renewable electricity generation (TWh)	0.167**	0.0801	0.039	0.233***	0.094	0.013
GDP index	0.249*	0.148	0.093	0.139	0.084	0.102
Electricity price (€/kWh)	− 38.48	37.94	0.311	5.417	31.55	0.864
Constant	− 33.86***	12.55	0.007	− 28.71***	8.59	0.001
Country fixed effects	Yes			Yes		
Period-country fixed effects[a]	No			Yes		
Observations	284			284		
Within R-squared	0.223			0.710		
Number of countries	20			20		

*** $p < 0.01$.
** $p < 0.05$.
* $p < 010$.
[a] Period-country fixed effects refer to dummy variables for each country i that are equal to one for country i during the period 2009–2015 and zero otherwise.

6. Conclusions and policy implications

Certification schemes have been introduced in renewable energy markets to address the problem of information asymmetry. Information asymmetry is an inherent market failure in energy markets because consumers cannot credibly distinguish between renewable and non-renewable energy. While certification is currently predominantly present in electricity markets, certification is expected to play an increasingly important role in other energy markets once renewable production comes off the ground in those markets (e.g. natural gas, hydrogen). Therefore, it is important to verify whether certification schemes prove an effective mechanism to facilitate trade in renewable energy and investigate how these schemes can be designed effectively.

The purpose of this paper is to investigate the performance of certificate markets and analyse the relationship between certificate system design and market performance. We apply our analysis to the market for electricity GO certification in twenty European countries. We evaluate market performance by analysing (1) the share of certified renewable electricity, (2) the churn rate, (3) price volatility and (4) the share of expired certificates (a measure for 'excess' supply). We use panel data to assess the effect on market performance of two critical design features of certificate systems: the public/private nature of certifiers and the presence of a common international standard.

Overall, our results suggest that markets for GOs remain in their infancies. The share of renewable electricity that receives certification has increased in the EU as a whole and in most individual countries since 2001. However, the other performance indicators yield a more pessimistic view. Market liquidity as measured by the churn rate is very poor and far below levels which are generally associated with a mature and liquid market, both in the region as a whole and in all individual countries. With respect to price volatility, GO certificate prices are very volatile and there are no clear signs of improvement over time. In addition to poor liquidity and high price volatility, the market appears to have been in a constant state of oversupply as a considerable amount of issued certificates is never used to claim the consumption of renewable electricity.

Our analysis indicates that certification-scheme design choices affect market outcomes. We find that adopting a common international standard has a strong positive affect on market volumes. Moreover, we find some evidence that private certifiers are associated with lower market volumes, which may be due to the higher certification fees that they appear to charge.

A number of data-related caveats of our analysis should be mentioned. First of all, our certification database is incomplete as observations for two countries were partly missing. Second, a few errors were discovered in the certification data. Although serious, we believe that we were able to handle these errors and obtained meaningful results. Thirdly, due to a lack of transparency in market prices, we rely on GO prices from a market monitoring firm. In case these prices are not representative for the market, some of our results may not be representative for the market. Therefore, we recommend to improve the availability of data for certificate markets as this would facilitate both market liquidity and the research on renewable energy markets.

Several policy implications can be drawn from this analysis. We found that European certificate markets are not yet functioning efficiently. With respect to certificate system design, international standardization of certificates contributes to the efficiency of certificate markets. Public ownership over the certifier may also have a positive effect although further research is required to corroborate this finding. In addition, policies that aim to improve market transparency may benefit the performance of certificate markets. The current lack of transparency, particularly regarding prices, may harm the confidence of market participants with respect to price formation and deter market entry.

Acknowledgements

We thank Phil Moody from the Association of Issuing Bodies for data support and an anonymous referee for helpful comments. This work was supported by the European Commission, Belgium [grant No. 691717].

Declaration of interest

None.

Appendix A. Descriptive statistics

(See Tables A1 and A2)

Table A1
Descriptive statistics for all variables except for GO certificate prices (all yearly averages), 2001–2016.
Sources: Certification: AIB; Renewable electricity production, electricity price (both except for Switzerland) and GDP index: Eurostat; Swiss renewable electricity production: IEA; Swiss electricity price: Swiss Federal Office of Energy.

		2001–2004	2005–2008	2009–2012	2013–2016
Certification					
Issued volume (TWh)					
	min	0.00	0.00	0.00	0.00
	max	8.26	111.08	135.70	136.11
	mean	0.81	5.57	10.83	18.82
	SD	1.88	16.58	25.94	30.43
Cancelled volume (TWh)					
	min	0.00	0.00	0.00	0.00
	max	7.55	28.75	43.81	87.59
	mean	0.38	3.06	9.86	15.85
	SD	1.23	6.34	13.22	19.70
Domestically transferred volume (TWh)					
	min	0.00	0.00	0.00	0.00
	max	0.54	39.58	43.76	88.99
	mean	0.03	1.00	4.67	11.98
	SD	0.10	4.71	9.18	20.57
Expired volume (TWh)					
	min	0.00	0.00	0.00	0.00
	max	0.54	39.58	43.76	88.99
	mean	0.03	1.00	4.67	11.98
	SD	0.10	4.71	9.18	20.57
Imported volume (TWh)					
	min	0.00	0.00	0.00	0.00
	max	8.35	28.14	52.89	80.31
	mean	0.21	2.15	8.22	14.31
	SD	1.23	4.97	13.12	20.50
Exported volume (TWh)					
	min	0.00	0.00	0.00	0.00
	max	6.43	50.54	134.49	161.82
	mean	0.20	2.03	8.10	14.19
	SD	0.94	7.08	21.83	29.29
Renewable electricity production (TWh)					
	min	0.01	0.01	0.04	0.32
	max	131.39	142.97	159.98	203.70
	mean	31.05	35.21	42.21	50.75
	SD	34.20	38.61	44.16	54.07
Electricity price (€/kWh)					
	min	0.05	0.07	0.09	0.11
	max	0.23	0.27	0.30	0.31
	mean	0.13	0.15	0.18	0.19
	SD	0.04	0.05	0.05	0.05
GDP index					
	min	75.30	88.30	94.20	90.20
	max	100.60	121.20	112.20	149.70
	mean	88.02	99.90	100.36	105.71
	SD	5.84	5.68	2.72	9.60

Table A2
Descriptive statistics of GO certificate spot prices (all yearly averages; Eurocent/MWh), 2011–2017.
Source: Greenfact.

Location	Technology		2011	2012	2013	2014	2015	2016	2017
Belgium	Biomass								
		min						38.00	19.20
		max						38.00	54.37
		mean						38.00	36.40
		SD							8.71
	Solar								
		min							35.00
		max							84.71
		mean							58.28
		SD							23.31
	Wind								
		min							27.00
		max							103.24
		mean							56.19
		SD							28.67
EU (unspecified)	Biomass								
		min	26.07	10.85	10.93	4.88	5.81	9.85	12.07
		max	26.66	27.01	10.93	11.50	9.05	24.50	28.00
		mean	26.36	20.06	10.93	7.43	7.62	18.15	20.50
		SD	0.42	7.41		2.92	1.18	4.44	5.21
	Hydro								
		min					4.62	10.50	14.00
		max					24.00	31.25	41.84
		mean					9.80	20.28	24.97
		SD					5.13	6.43	7.43
	Solar								
		min					15.00	22.38	15.15
		max					21.86	54.15	46.71
		mean					19.08	43.92	25.84
		SD					2.57	12.61	9.86
	Wind								
		min	25.75	11.00	9.00	4.50	5.86	18.50	15.51
		max	66.93	48.00	30.55	38.93	18.87	37.05	44.00
		mean	40.94	34.05	19.36	19.71	14.17	24.58	27.36
		SD	16.61	14.01	9.19	13.54	4.53	5.79	8.37
Italy	Hydro								
		min					7.25	15.77	14.00
		max					18.00	29.00	41.67
		mean					10.57	21.26	26.06
		SD					3.77	3.85	9.26
Netherlands	Biomass								
		min						45.00	23.00
		max						45.00	66.50
		mean						45.00	36.26
		SD							13.18
	Solar								
		min							225.00
		max							365.00
		mean							280.00
		SD							74.67
	Wind								
		min							233.40
		max							451.50
		mean							315.73
		SD							73.22
Nordic	Hydro								
		min	18.83	12.33	8.60	4.56	4.97	14.66	19.40
		max	62.02	40.08	22.65	10.59	11.73	33.15	39.77
		mean	42.45	27.47	15.10	6.57	8.06	21.75	25.88
		SD	14.30	8.60	4.51	2.10	1.95	6.50	5.51
Switzerland	Hydro								
		min							70.38
		max							496.99
		mean							282.22
		SD							171.74

Appendix B. Construction of churn rates and data issues

In the Czech Republic, Finland and Italy, the churn rates based on cancellations spike to unrealistically high levels in the very first year of operation (e.g. 30 in Finland). These rates all drop after the first year and both churn rates based on issuance do not spike. The majority of these certificates was most probably cancelled (or expired) in the next year, thereby inflating the churn rate based on cancellations in the first year of operation. For these three countries, we can be quite certain that the spikes are caused by the way we constructed the churn rates.

For Germany, both the churn rate based on issuance and previous year's issuance spike in 2002 to more than 1000 and 3000 respectively. These spikes are caused by an extremely high level of domestic transfers (more than 513,000) in 2002. In 2001 and 2002 combined, there were less than 600 certificates issued and no imports at all. Moreover, no transfers at all were conducted in Germany in any other year between 2001 until 2007. Also, no cancellations occurred until 2004. This gives sufficient reason to believe that the number of 513,000 transfers does not represent the actual traded volume in Germany in 2002.

In Iceland, the churn rate based on cancellations spikes to 243 in 2015 (coming from 0.37 in the previous year). This is caused by a concurrent decrease in cancelled volume of 89% and massive increase in transferred volume of 7410%. We cannot conclude that our calculation method causes the spike nor that it is caused by suspicious reporting. Two signals that the spike does not represent the actual state of liquidity in 2015 are: (i) the other two churn rates in that year take on plausible values and (ii) the churn rate based on cancellations drops again to 1.8 in 2016. Moreover, even in the most mature and liquid markets, churn rates of 243 are rarely observed. Therefore, we omit this observation.

Appendix C. Correlation coefficients between certificate spot price series

(See Table C1)

Table C1
Correlation coefficients between certificate spot price series, 2011–2017.

	Nordic Hydro	EU Biomass	EU Hydro	EU Solar	EU Wind	IT Hydro
Nordic Hydro						
EU Biomass	0.84					
EU Hydro	0.12	− 0.03				
EU Solar	0.86	0.92	0.04			
EU Wind	0.57	0.58	− 0.14	0.57		
IT Hydro	0.63	0.84	0.01	0.78	0.44	

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